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# EFFECTS OF GEOMETRIC AND MATERIAL PARAMETERS ON BEHAVIOR OF FIBER COMPOSITES

FINAL REPORT

by

I. M. Daniel

McCormick School of Engineering and Applied Science
Northwestern University
Evanston, IL 60208

for

Air Force Office of Scientific Research
Bolling AFB, DC 20332

May 1996

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## Foreword

This is the Final Report on project "Effects of Geometric and Material Parameters on Behavior of Fiber Composites," prepared by Northwestern University for the Air Force Office of Scientific Research (AFOSR) under Grant No. F49620-0313DEF. The work described in this report was conducted in the period June 1, 1992 to December 14, 1995. Dr. Walter F. Jones was the AFOSR project manager. The project was directed by Professor I. M. Daniel with Mr. R. D. Cordes, Research Assistant, as a principal contributor.

Northwestern University

I. M. Daniel
Professor
Theoretical and Applied Mechanics

# EFFECTS OF GEOMETRIC AND MATERIAL PARAMETERS ON BEHAVIOR OF FIBER COMPOSITES

## 1. INTRODUCTION

The objective of this investigation is to study the effects of constituent properties (fiber, matrix, interphase) and geometric parameters (fiber volume ratio, fiber packing) on the overall behavior of brittle matrix composites. The understanding of the effects of all these parameters is incomplete. One reason for this is the inability to control or fully characterize some properties, especially the in-situ properties of the matrix and interphase/interface.

The nature of the bond between fiber and matrix, whether occurring through a zero-thickness interface or an interphase region, plays a profound role on failure mechanisms, toughness and overall deformation behavior of the composite. Characterization of this interphase is a very challenging problem. There are no easy direct means for characterizing the interphase and thereby evaluating its effects. Indirect means can be used for interphase characterization, by correlating interphase properties to observed microscopic failure mechanisms and macroscopic stress-strain behavior. Strength properties of the interphase, such as interfacial shear strength, can be correlated to observed microscopic failure mechanisms, such as matrix crack density, applied stress at crack initiation and distance between matrix and fiber cracks.

The strength of the interphase and the overall behavior of the composite are affected greatly by the state of residual stress. It is therefore important to develop methods to determine residual stresses in the composite.

Ultimately, it is desired to develop a realistic analytical model verified by testing prototype materials. This can be enhanced greatly by developing and testing

model composites. Model materials have the distinct advantage that they are amenable to control and variation of the relevant parameters. For this reason significant effort was directed toward this end.

## 2. TECHNICAL PROGRESS [1]

### 2.1 Model Materials

The objective of this task was to develop and characterize model brittle-matrix composite materials, i.e., composites with a matrix having a lower ultimate strain than that of the fiber. Model materials enable control of many material and geometric parameters for the study of their effects on failure mechanisms and overall stress-strain behavior.

Four model materials were developed and fabricated. They include:

(1) Silicon carbide fiber/barium borosilicate glass system.

(2) Polyvinyl-alcohol fiber/epoxy system.

(3) Acrylate-coated optic fiber/epoxy system.

(4) Polyimide-coated optic fiber/epoxy system.

### 2.2 Interfacial Properties

Single-fiber specimens were tested by pulling out the fiber and observing the onset and progression of debonding and sliding. A typical record of progressive debonding and pullout for a silicon carbide fiber in a glass matrix is shown in Fig. 1 [2]. Debonding starts at the free end of the matrix and propagates towards the embedded end of the fiber as the load is increased monotonically. The peak load is reached upon completion of debonding at which point a sudden drop in load occurs and pullout begins.

Models such as the one proposed by Kerans and Parthasarathy [3] were reviewed and used to interpret the experimental results. In view of the varying

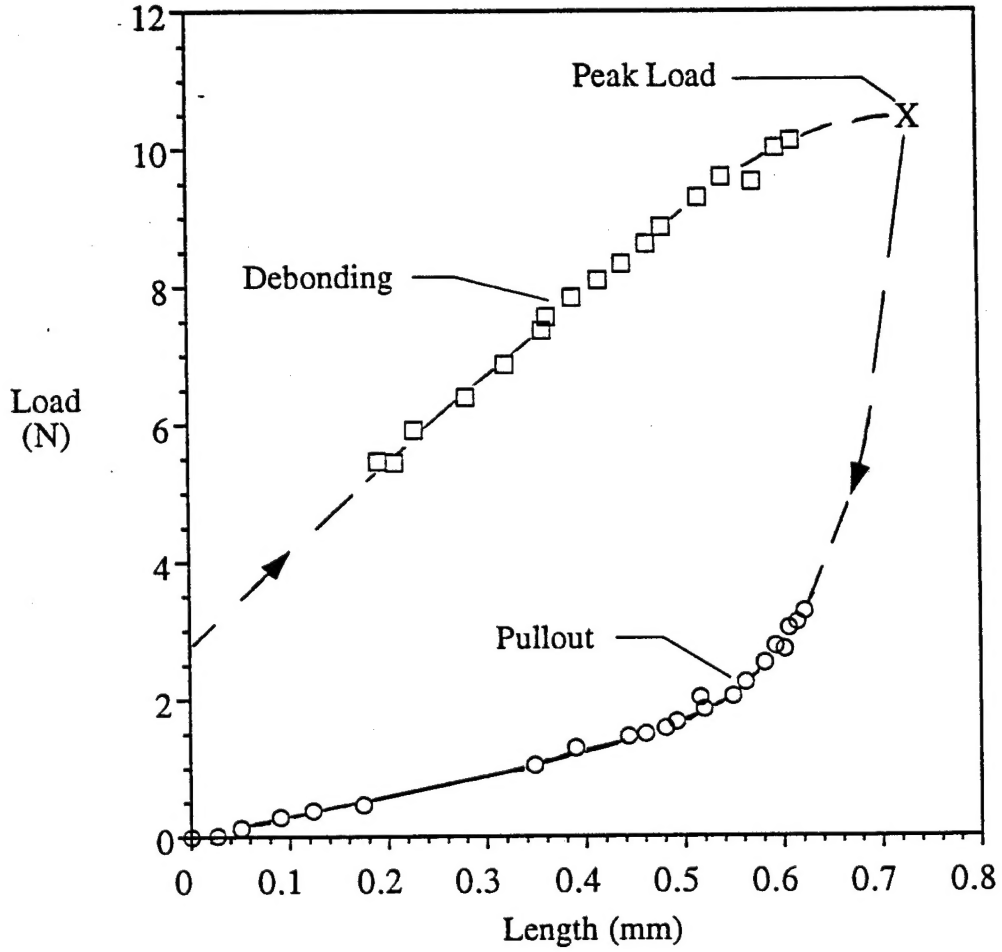


Fig. 1 Load vs. Debonded Length during Debonding and Load vs. Embedded Length during Pullout

coefficient of friction during pullout, as manifested by the nonlinear load versus embedded length curve, revised models were considered incorporating the effects of fiber surface asperities and wear during pullout.

### 2.3 Multiple Fiber Composite Models

In the case of the silicon carbide/glass system, results of tensile tests were similar to those found in ceramic matrix composites. They showed linear elastic response followed by multiple matrix cracking and transverse strain reversal. Debonding accompanied the matrix cracking and increased in magnitude with applied load.

In the case of the polyvinyl-alcohol fiber/epoxy specimens, the fiber-matrix bond was weak but the pronounced roughness of the fiber surface led to extensive matrix cracking and debonding. Debonding appeared at the onset of matrix cracking extending a distance from the matrix crack which increased with the load.

Of the two optic fiber systems tested, the polyimide-coated fiber had a stronger bond to the matrix than the acrylate-coated one. The polyimide-coated glass fibers produced high crack densities. The matrix cracks were observed to initiate at the fiber-matrix interface. Typical stress-strain curves are shown in Fig. 2. Matrix cracking produces the "zig-zag" features in the curve.

The effects of fiber volume ratio and postcuring were also investigated. One important observation was that the applied strain at crack initiation was always higher than the ultimate strain of the bulk matrix epoxy by over 30%. This "in-situ" ultimate strain increased further with increasing fiber volume ratio. Heat treatment (or postcuring) was found to increase the ultimate strain of the matrix, both in bulk form and within the composite. A typical stress-strain curve of a heat-treated composite of fiber volume ratio comparable to that of Fig. 2 is shown in Fig. 3. It is noted that the first evidence of matrix cracking occurs at a strain of approximately 3%, double that of the room-temperature cured specimen (Fig. 2).

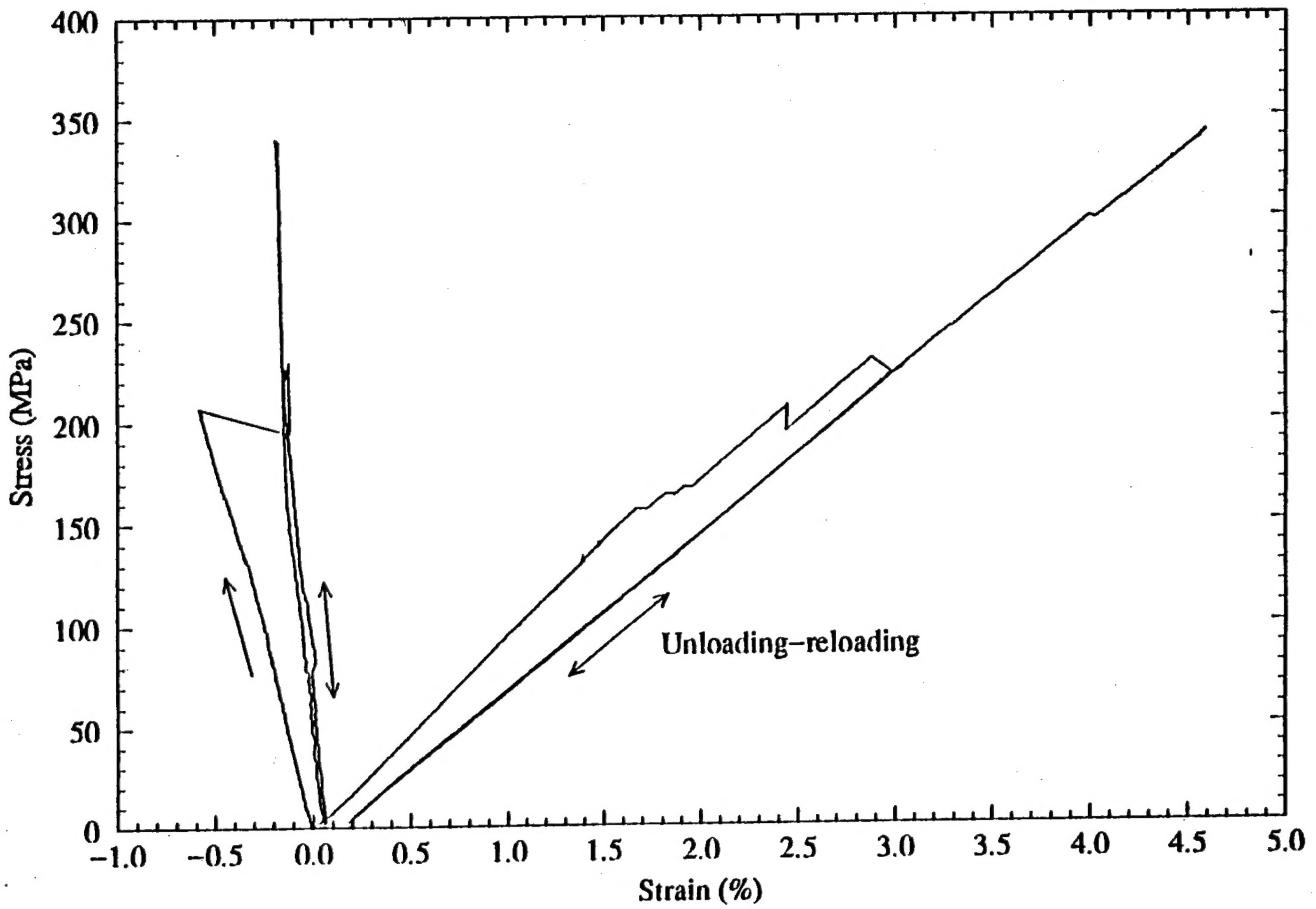


Fig. 2 Stress versus Strain for FOP/Epoxy Composite with no Heat Treatment (volume fraction = 11.6%)

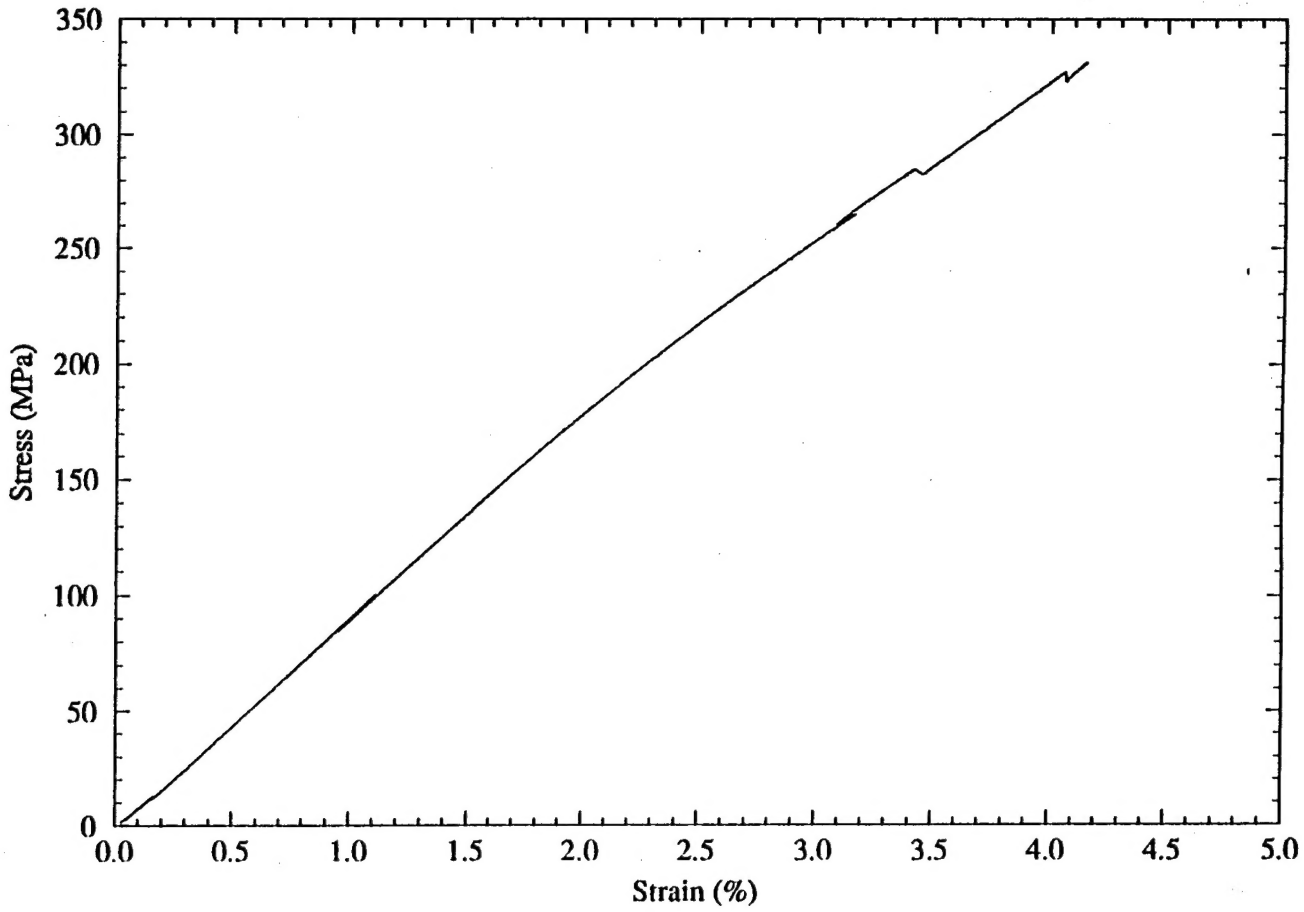


Fig. 3 Stress versus Strain for FOP/Epoxy Composite Heat Treated to 56.7 C (134 F) (volume fraction = 10.5%)

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